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# 3D SOLID ELEMENT (TYPE 4—ELASTIC OR ELASTIC-PERFECTLY-PLASTIC) FOR THE ANSR-II PROGRAM

by
DIGAMBAR P. MONDKAR
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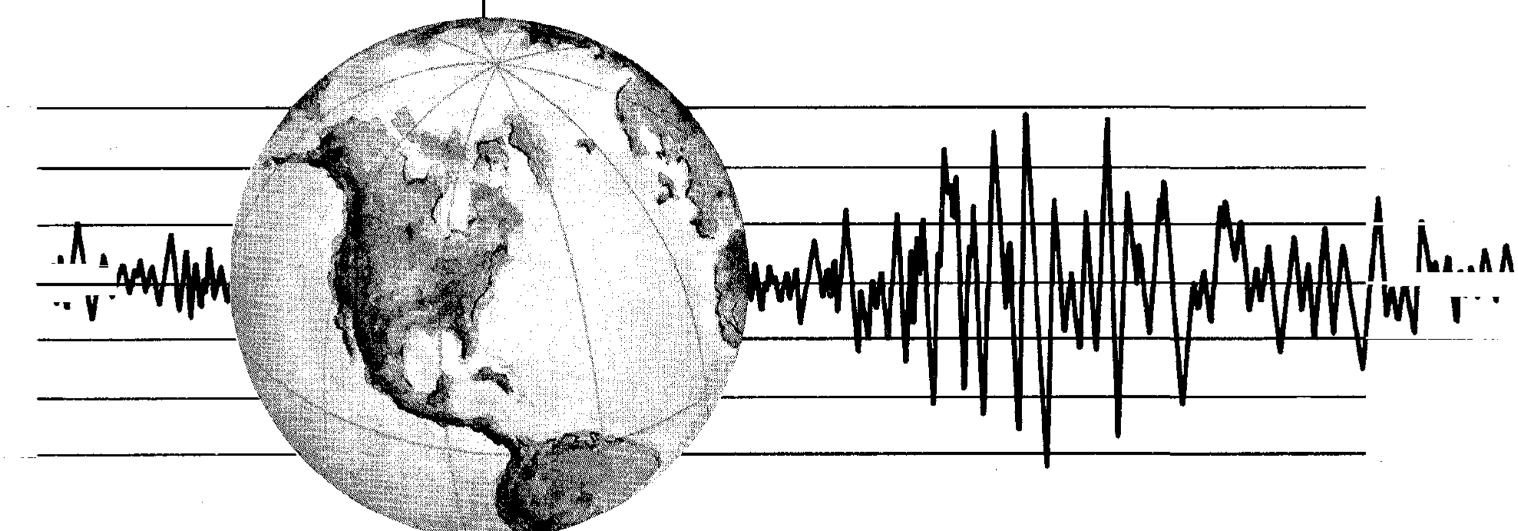

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# 3D SOLID ELEMENT

# (TYPE 4 - ELASTIC OR ELASTIC-PERFECTLY-PLASTIC)

# FOR THE ANSR-II PROGRAM

by

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Report to
National Science Foundation
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## ABSTRACT

This report describes a three-dimensional nonlinear finite element developed for the ANSR-II program. The report contains a description of the element characteristics, the theoretical formulation, and a computer program user's guide.

## ACKNOWLEDGEMENTS

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# 1. INTRODUCTION

This report describes a three-dimensional, nonlinear solid finite element for the ANSR-II code [1]. The element has the following features:

(1) Arbitrary orientation in space.

(2) Variable number of nodes (from 8 to 20).

(3) Large displacement effects may be included or ignored. These effects are based on a total Lagrangian formulation.

(4) Variable Gauss integration order (from 1 to 4 points in each of the three local directions).

(5) Choice of three material models, namely:

  (a) Isotropic linearly elastic material.

  (b) Orthotropic linearly elastic material.

  (c) Elastic-perfectly plastic material with von Mises yield criterion.

(6) For dynamic analysis, damping proportional to initial elastic stiffness and/or current tangent stiffness.

(7) Stress and strain output at Gauss integration points plus one other user-specified point.

This report contains a description of the element and the element user's guide.

## 2. ELEMENT PROPERTIES

3D solid finite elements may be arbitrarily oriented in space.

Each element can have from eight to twenty nodes. There are three translational degrees of freedom (X, Y, Z translations) at each node. The element maps into a prism in a local r-s-t coordinate system, such that nodes 1 through 8 are located at the corners and nodes 9 through 20 are located at midsides of the edges of the prism (Fig. 1). The eight corner nodes must always be specified, and any one or more of the mid-side nodes may be specified.

The element matrices (stiffness, resisting nodal loads, etc.) are computed using Gauss quadrature integration. The integration order (number of integration points) in each of the local r-s-t directions may be specified separately (from one to four points in each direction). For most cases, $2 \times 2 \times 2$ integration is recommended.

Large displacement effects may be included or ignored. If large displacements are considered, a total Lagrangian formulation is used.

Three different material models are included, as follows:

(a) Isotropic linearly elastic material.

(b) Orthotropic linearly elastic material.

(c) Elastic-perfectly-plastic material, with von Mises yield criterion.

Orthotropic material properties are defined with respect to the global axes. For the elastic-perfectly plastic material, the stress increment during plastic loading is obtained by dividing the strain increment into a number of subincrements, and performing Runge-Kutta integration in each subincrement. For most applications, a single increment and first order (Euler) integration will be sufficient.

For results output, stresses and strains at a user-specified "output" point are printed. The r-s-t coordinates of the output point may be input by the user, with default at the element center (r = s = t = 0). In addition, the results at the Gauss integration points may be printed.

# 3. THEORY

## 3.1 LARGE DISPLACEMENT FORMULATION

### 3.1.1 General

The large displacement formulation for a general finite element system in a Lagrangian reference frame has previously been presented [e.g. 2,3]. The strain-displacement relationships and element stiffness matrices are developed as the structure deforms from a known state (configuration 1, time t) to a neighboring state (configuration 2, time t + $\Delta$t). All strain and stress quantities in the deformed configurations are referred to the undeformed state (configuration 0, time = 0).

In the following sections, the large displacement formulation for a 3D solid finite element will be briefly presented, following procedures outlined in detail in the previous reports [e.g. 2,3].

### 3.1.2 Shape Functions

For a 20-node isoparametric element (Fig. 1), the shape functions can be written as follows:

(a) For corner nodes ($m$ = 1 to 8, $r_m = \pm 1$, $s_m = \pm 1$):

$$
\begin{aligned}
N^m(r,s,t) = {} & \frac{1}{8}(1+r r_m)(1+s s_m)(1+t t_m) \\
& -\frac{1}{8}\ (1-r^2)(1+s s_m)(1+t t_m) + (1+r r_m)(1-s^2)(1+t t_m) \\
& + (1+r r_m)(1+s s_m)(1-t^2)
\end{aligned}
\qquad (1)
$$

(b) For midside nodes ($m$ = 9 to 20):

$$N^m(r,s,t) = \frac{1}{4}(1-r^2)(1+s s_m)(1+t t_m)\,, \quad r_m = 0 \qquad (2)$$

$$N^m(r,s,t) = \frac{1}{4}(1+r r_m)(1-s^2)(1+t t_m)\,, \quad s_m = 0 \qquad (3)$$

$$N^m(r,s,t) = \frac{1}{4}(1+r r_m)(1+s s_m)(1-t^2), \quad t_m = 0 \qquad (4)$$

For a variable (8 to 20) node element, the shape functions for the midside nodes are included only for those nodes which are present. For the corner nodes, terms involving $(1-r^2)$, $(1-s^2)$, and $(1-t^2)$ in Eqn. (1) are included only if corresponding midside nodes are present (e.g. if only node 17 is present, the shape function for node 17 will be obtained from Eqn. (4), and the shape functions for nodes 1 and 5 will have terms involving $(1-t^2)$ included).

Following standard finite element methodology [4], the global X, Y, and Z displacements at any point within the element, in the current deformed state 1, are related to the nodal displacements as follows:

$$\{{}^1u\} = [N]\{{}^1q\} \tag{5}$$

in which $\{{}^1u\}$ is the vector of displacements within the element, $[N]$ is the matrix of shape functions, and $\{{}^1q\}$ is the vector of nodal displacements.

Similarly, displacement increments from the deformed state 1 to the deformed state 2 are related to the nodal displacement increments as follows:

$$\{u\} = [N]\{q\} \tag{6}$$

In subsequent relationships, derivatives of the shape functions with respect to the global X-Y-Z axes will be needed. These derivatives are obtained by the usual Jacobian transformation [4].

### 3.1.3 Stress-Strain Components

The state of stress at a point within the element is described by six components, namely ${}^1S_{xx}$, ${}^1S_{yy}$, ${}^1S_{zz}$, ${}^1S_{xy}$, ${}^1S_{yz}$, and ${}^1S_{zx}$ in the deformed state 1 (time t).

The corresponding strain components are ${}^1E_{xx}$, ${}^1E_{yy}$, ${}^1E_{zz}$, $2{}^1E_{xy}$, $2{}^1E_{yz}$, and $2{}^1E_{zx}$.

#### 3.1.4 Strain-Displacement Transformation

The increment of strain, $\{E\}$, from deformed configuration 1 to the deformed configuration 2 is decomposed into a linear part, $\{e\}$, and a nonlinear part, $\{\eta\}$. That is,

$$\{E\} = \{e\} + \{\eta\} \tag{7}$$

The linear part is related to the nodal displacements through the following relationship:

$$\{e\} = [{}^1F]\,\{u_\partial\} \tag{8}$$

in which $[{}^1F]$ is the matrix of deformation gradients and $\{u_\partial\}$ is the vector of displacement gradients. The matrix $[{}^1F]$ is easily obtained from Eqn. 2.15 of Reference 3. The vector $\{u_\partial\}$ is obtained from Eqn. (6) as follows:

$$\{u_\partial\} = [N_\partial]\,\{q\} \tag{9}$$

in which $[N_\partial]$ is the matrix of derivatives of shape functions.

Combining Eqns. (8) and (9), the following strain-displacement relationship is obtained

$$\{e\} = [{}^1F]\,[N_\partial]\,\{q\} \tag{10a}$$

or

$$\{e\} = [{}^1B]\,\{q\} \tag{10b}$$

An explicit relationship (such as in Eqn. (10)) between nonlinear strain and displacement increments is not needed, as explained subsequently.

### 3.1.5 Element Stiffness Matrix

The element stiffness matrix is given by

$$K_E = \int_{V_o} [{}^1B]^T \, [C] \, [{}^1B] \, dV \tag{11}$$

in which $[C]$ is the material constitutive matrix, and $V_o$ is the volume of the element in the undeformed state. The integration in Eqn. (11) is carried out numerically using Gauss quadrature.

### 3.1.6 Geometric Stiffness Matrix

The nonlinear part of the strain increment is given by

$$\begin{aligned} \eta_{xx} &= \frac{1}{2}\left[\left(\frac{\partial u_x}{\partial x}\right)^2 + \left(\frac{\partial u_y}{\partial x}\right)^2 + \left(\frac{\partial u_z}{\partial z}\right)^2\right] \\ \eta_{xy} &= \frac{1}{2}\left[\left(\frac{\partial u_x}{\partial x}\right)\left(\frac{\partial u_x}{\partial y}\right) + \left(\frac{\partial u_y}{\partial x}\right)\left(\frac{\partial u_y}{\partial y}\right) + \left(\frac{\partial u_z}{\partial x}\right)\left(\frac{\partial u_z}{\partial y}\right)\right] \end{aligned} \tag{12}$$

Similar expressions can be written for $\eta_{yy}$, $\eta_{zz}$, $\eta_{yz}$, $\eta_{zx}$ by permutation of subscripts x, y, z.

The geometric stiffness, $[K_G]$, of the element is obtained from the virtual work equation

$$\begin{aligned} \{\delta q\}^T \, [K_G] \, \{q\} = \int_{V_o} ( & {}^1S_{xx} \, \delta\eta_{xx} + {}^1S_{yy} \, \delta\eta_{yy} + {}^1S_{zz}\delta\eta_{zz} \\ & + 2\,{}^1S_{xy} \, \delta\eta_{xy} + 2\,{}^1S_{yz} \, \delta\eta_{yz} + 2\,{}^1S_{zx} \, \delta\eta_{zx})dV \end{aligned} \tag{13}$$

in which $\delta(\cdot)$ is a variation on the undesignated variable.

By combining Eqns. (12) and (13) and simplifying, it can be shown that

$$[K_G] = \int_{V_o} [N_\partial]^T \; [{}^1\hat{S}] \; [N_\partial] \; dV \tag{14}$$

in which the matrix of shape function derivatives $[N_\partial]$ is defined in Eqn. (9), and the matrix $[^1\hat{S}]$ is as follows:

$$[\hat{S}] = \begin{bmatrix} [^1S] & 0 & 0 \\ 0 & [^1S] & 0 \\ 0 & 0 & [^1S] \end{bmatrix} \tag{15}$$

in which

$$[^1S] = \begin{bmatrix} {}^1S_{xx} & {}^1S_{xy} & {}^1S_{zx} \\ {}^1S_{xy} & {}^1S_{yy} & {}^1S_{yz} \\ {}^1S_{zx} & {}^1S_{yz} & {}^1S_{zz} \end{bmatrix} \tag{16}$$

As for the element stiffness matrix, the integral in Eqn. (14) is evaluated numerically using Gauss quadrature.

#### 3.1.7 Equilibrium Nodal Loads

Nodal loads in equilibrium with the state of stress in the deformed state at time t are given by

$$\{^1R\} = \int_{V_0} [^1B]^T \{^1S\} \, dV \tag{17}$$

in which $\{^1S\}^T = < {}^1S_{xx} \; {}^1S_{yy} \; {}^1S_{zz} \; {}^1S_{xy} \; {}^1S_{yz} \; {}^1S_{zx} >$ and the strain-displacement transformation matrix $[^1B]$ is given in Eqn. (10b). Again, the integral in Eqn. (17) is evaluated numerically.

## 3.2 MATERIAL MODELS

### 3.2.1 General

Three different material models are included, as follows:

(a) Isotropic linearly elastic material.

(b) Orthotropic linearly elastic material.

(c) Elastic-perfectly plastic material, with von Mises yield criterion.

The constitutive relationship between increments of stress and strain can be written as

$$\begin{Bmatrix} S_{xx} \\ S_{yy} \\ S_{zz} \\ S_{xy} \\ S_{yz} \\ S_{zx} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ & & C_{33} & C_{34} & C_{35} & C_{36} \\ & & & C_{44} & C_{45} & C_{46} \\ & & & & C_{55} & C_{56} \\ \text{Symmetric} & & & & & C_{66} \end{bmatrix} \begin{Bmatrix} E_{xx} \\ E_{yy} \\ E_{zz} \\ 2E_{xy} \\ 2E_{yz} \\ 2E_{zx} \end{Bmatrix} \qquad (18)$$

That is,

$$\{S\} = [C]\{E\}$$

It should be noted that for large displacements the above relationship is assumed to be between the (second) Piola-Kirchhoff stress and Green-Lagrange strain.

3.2.2 Isotropic Linearly Elastic Material

For this material the coefficients of matrix $[C]$ are as follows:

$$\begin{aligned} C_{11} &= C_{22} = C_{33} = 2\mu + \lambda \\ C_{12} &= C_{13} = C_{23} = \lambda \\ C_{44} &= C_{55} = C_{66} = \mu \end{aligned} \qquad (19)$$

All other coefficients are zero. The constants $\lambda$ and $\mu$ are

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)} \quad \text{and} \quad \mu = \frac{E}{2(1+\nu)} \tag{20}$$

in which E = Young's modulus and $\nu$ = Poisson's ratio.

3.2.3 Orthotropic Linearly Elastic Material

Orthotropic material constants are defined with respect to the global X-Y-Z axes. The constitutive relationship for this material can be written as

$$\{E\} = \left[C\right]^{-1} \{S\} = \left[D\right] \{S\} \tag{21}$$

in which the coefficients of matrix $\left[D\right]$ are

$$\begin{aligned} D_{11} &= 1/E_x; \quad D_{22} = 1/E_y; \quad D_{33} = 1/E_z; \\ D_{12} &= -\nu_{xy}/E_y; \quad D_{13} = -\nu_{xz}/E_z; \\ D_{23} &= -\nu_{yz}/E_z; \\ D_{44} &= 1/G_{xy}; \quad D_{55} = 1/G_{yz}; \quad D_{66} = 1/G_{zx} \end{aligned} \tag{22}$$

Nine material constants, namely the moduli of elasticity $E_x$, $E_y$, $E_z$; Poisson's ratios $\nu_{xy}$, $\nu_{xz}$, $\nu_{yz}$; and the shear moduli $G_{xy}$, $G_{yz}$, $G_{zx}$ define the material. The matrix $\left[C\right]$ is obtained by inverting matrix $\left[D\right]$.

3.2.4 Elastic-Perfectly-Plastic Material

The flow theory of plasticity and the von Mises yield criterion are used to derive the constitutive relationship. Details of the derivation can be found in Reference 2. The elastic-perfectly-plastic constitutive matrix is given as

$$\left[C\right] = \left[C^E\right] - \left[C^P\right] \tag{23}$$

in which $\left[C^E\right]$ is defined by Eqn. (19) and the matrix $\left[C^P\right]$ is as follows:

$$\left[C^P\right] = \frac{3\mu}{\sigma_y^2} \{\bar{S}\} \{\bar{S}\}^T \tag{24}$$

in which

$$\{\bar{S}\}^T = < \bar{S}_{xx} \; \bar{S}_{yy} \; \bar{S}_{zz} \; S_{xy} \; S_{yz} \; S_{zx} > \tag{25}$$

$$\begin{aligned} \bar{S}_{xx} &= S_{xx} - \sigma_m \\ \bar{S}_{yy} &= S_{yy} - \sigma_m \\ \bar{S}_{zz} &= S_{zz} - \sigma_m \end{aligned} \tag{26}$$

$\sigma_y$ = Yield stress in uniaxial tension or compression

$\sigma_m$ = Mean stress = $\frac{1}{3} (S_{xx} + S_{yy} + S_{zz})$

## 3.3 STATE DETERMINATION CALCULATION

"State determination" involves computation of the stress increments for given strain increments. For linearly elastic isotropic and orthotropic materials, the stress increments are obtained by applying Eqn. (18). For an elastic-perfectly-plastic material, the state of stress, computed assuming elastic behavior during any load step, may lie outside the yield surface. This is not admissible and must be corrected.

As an example, let point A (Fig. 2) define the state of stress at the beginning of a load step. Assuming linear behavior within the step, let the new state of stress be at point D, which is outside the yield surface and is, therefore, not admissible. Assuming that strains vary proportionately within the step, a stress state (point B) is computed where the stress path intersects the yield surface. For the remainder of the strain

increment, the stress increment from point B to point C is computed as follows:

(a) The increment is divided into a number of equal subcrements. This number is specified by the user.

(b) The stress increment for each strain subincrement is computed using Runge-Kutta integration of up to fourth order. The order of integration is specified by the user.

If large plastic strain increments can occur within a load or time step, it may be desirable to specify several subincrements. For most applications, however, it is recommended that the number of subincrements be at most 2 and that Euler integration (order = 1) be used.

## 4. RESULTS OUTPUT

The following results are printed at the specified output intervals in static and dynamic analyses for those elements for which response results are requested.

(1) Element number.

(2) For the output point:

(a) Yield code: zero elastic; 1 = yielding.

(b) Stress components: SIG11, SIG22, SIG33, SIG12, SIG23, and SIG 31.

(c) Strain components: STR11, STR22, STR33, STR12, STR23, and STR31.

(d) Effective stress, EFFSIG, given by

$$\text{EFFSIG} = \sqrt{1.5\ \text{YSS}}$$

where

$$\text{YSS} = (\text{SIG11})^2 + (\text{SIG22})^2 + (\text{SIG33})^2 + 2(\text{SIG12})^2 + 2(\text{SIG23})^2 + 2(\text{SIG31})^2$$

(3) If results at the Gauss integration points are to be printed, results 2(a) through 2(d) are printed at each point.

The results envelopes consist of the following:

(1) Element number.

(2) Maximum positive and negative values of stress and strain components, and the corresponding times at which these peak values occur, at the output point and each Gauss point.

# 5. USER'S GUIDE

## 3D SOLID FINITE ELEMENT (TYPE 4)

### 5.1 CONTROL INFORMATION

Two Cards.

#### 5.1(a) First Card

| Columns | Note | Name | Data |
|---|---|---|---|
| 5(I) | | NGR | Element group indicator Punch 4. |
| 6-10(I) | (1) | NELS | Number of elements in group. |
| 11-15(I) | | MFST | Element number of first element in group Default = 1. |
| 16-25(F) | | DFO | Initial stiffness damping factor, $\beta_O$. |
| 26-35(F) | | DKT | Tangent stiffness damping factor, $\beta_T$. |
| 41-80(A) | | GRHED | Optional group heading. |

#### 5.1(b) Second Card

| Columns | Note | Name | Data |
|---|---|---|---|
| 1- 5(I) | (2) | NODES | Number of nodes describing each element (Min.= 8, Max.= 20). Default = 8. |
| 6-10(I) | | NMAT | Number of different material types. Default = 1. |
| 15(I) | (3) | MODEL | Material model number. No default.<br>(a) 1: Isotropic linearly elastic.<br>(b) 2: Orthotropic linearly elastic.<br>(c) 3: Elastic-perfectly plastic, with von Mises yield criterion. |
| 20(I) | (4) | IORDR | Gauss integration order in r-direction (Min.= 1, Max.= 4). Default = 2. |
| 25(I) | | IORDS | Gauss integration order in s-direction (Min.= 1, Max.= 4). Default = 2. |
| 30(I) | | IORDT | Gauss integration order in t-direction (Min.= 1, Max.= 4). Default = 2. |

## 5.2 MATERIAL PROPERTIES

### 5.2(a) Isotropic Linearly Elastic Material

NMAT cards. Omit this section if MODEL is not 1.

| Columns | Note | Name | Data |
|---|---|---|---|
| 1- 5(I) | | | Material type number. |
| 6-15(F) | | | Young's modulus, E. |
| 16-25(F) | | | Poisson's ratio, $\nu$. |

### 5.2(b) Orthotropic Linearly Elastic Material

NMAT cards. Omit this section if MODEL is not 2.

| Columns | Note | Name | Data |
|---|---|---|---|
| 1- 5(I) | | | Material type number. |
| 6-15(F) | (5) | | Young's modulus, $E_X$. |
| 16-25(F) | | | Young's modulus, $E_Y$. |
| 26-35(F) | | | Young's modulus, $E_Z$. |
| 36-40(F) | | | Poisson's ratio, $\nu_{XY}$. |
| 41-45(F) | | | Poisson's ratio, $\nu_{XZ}$. |
| 46-50(F) | | | Poisson's ratio, $\nu_{YZ}$. |
| 51-60(F) | | | Shear modulus, $G_{XY}$. |
| 61-70(F) | | | Shear modulus, $G_{YZ}$. |
| 71-80(F) | | | Shear modulus, $G_{ZX}$. |

### 5.2(c) Elastic-Perfectly Plastic Material

NMAT cards. Omit this section if MODEL is not 3.

| Columns | Note | Name | Data |
|---|---|---|---|
| 1- 5(I) | | | Material type number. |
| 6-15(F) | | | Young's modulus, E. |
| 16-25(F) | | | Poisson's ratio, $\nu$. |

| Columns | Note | Name | Data |
|---|---|---|---|
| 26-35(F) | | | Yield stress, $\sigma_Y$. |
| 36-45(I) | (6) | | Number of equal subincrements of strain for plastic loading. No default. |
| 46-55(I) | | | Order of Runge-Kutta integration (Min.= 1, Max.= 4). No default. |

## 5.3 ELEMENT DATA GENERATION

As many cards as needed to generate all elements in group.

### 5.3(a) First Card

| Columns | Note | Name | Data |
|---|---|---|---|
| 1- 5(I) | (7) | MEL | Element number, or number of first element in a sequentially numbered series of elements to be generated by this card. |
| 6-10(I) | | NODE1 | Node number 1. |
| 11-15(I) | | NODE2 | Node number 2. |
| 16-20(I) | | NODE3 | Node number 3. |
| 21-25(I) | | NODE4 | Node number 4. |
| 26-30(I) | | NODE5 | Node number 5. |
| 31-35(I) | | NODE6 | Node number 6. |
| 36-40(I) | | NODE7 | Node number 7. |
| 41-45(I) | | NODE8 | Node number 8. |
| 46-50(I) | | MAT | Material type number. Default = 1. |
| 51-55(I) | | INC | Node number increment for element generation. Default = 1. |
| 60(I) | | KGEOM | Large displacements code.<br>(a) zero or blank: small displacements<br>(b) 1: large displacements |
| 65(I) | | KTHO | Response output code.<br>(a) zero or blank: no print output<br>(b) 1: results at "output" point only<br>(c) 2: results at Gauss points in addition to "output" point |

| Columns | Note | Name | Data |
|---|---|---|---|
| 66-70(F) | | ROUT | Local r-coordinate of "output" point. Default = 0.0. |
| 71-75(F) | | SOUT | Local s-coordinate of "output" point. Default = 0.0. |
| 76-80(F) | | TOUT | Local t-coordinate of "output" point. Default = 0.0. |

5.3(b) Second Card

Omit this card if NODES = 8.

| Columns | Note | Name | Data |
|---|---|---|---|
| 1- 5(I) | | NODE9 | Node number 9. May be zero. |
| 6-60(I) | | | Node numbers 10 through 20 in 5-column fields. Blank or zero indicates node not to be considered. |

## 5.4 USER'S GUIDE NOTES

NOTE(1) The elements in group are numbered sequentially, starting with MFST (i.e. MFST, MFST+1, MFST+2, ..., MFST+NELS-1).

NOTE(2) Each element can have from 8 to 20 nodes (Fig. 1). However, all elements in group must have the same number of nodes. The eight corner nodes (1 through 8) must always be specified, and any one or more of the midside nodes (9 through 20) may be specified.

NOTE(3) All elements in group must have the same material model.

NOTE(4) Gauss integration orders from 1 to 4 may be specified separately in each of the r, s, and t directions (e.g. IORDR = 2, IORDS = 2, and IORDT = 3). All elements in any group must have the same integration order.

NOTE(5) Orthotropic material properties are defined with respect to the global X-Y-Z axes.

NOTE(6) Refer to Section 3.3 for explanations of the number of strain subincrements and the order of Runge-Kutta integration. For most applications a single increment and first order integration will be sufficient.

NOTE(7) Cards must be input in order of increasing element number. Cards for the first and last elements must be included (that is, data for these two elements cannot be generated).

Cards may be provided for all elements, in which case each card specifies the data for one element, and the generation option is not used. Alternatively, the cards for a series of elements may be omitted, in which case data for the missing elements is generated as follows:

(a) All missing elements are assigned the same material number (MAT), codes for large displacements and response output (KGEOM and KTHO), and "output" point coordinates as for the element preceding the missing series of elements.

(b) The node numbers (NODE1 through NODE8, and NODE9 through NODE20 if NODES > 8) for each missing element are obtained by adding the increment (INC) to node numbers of the preceding element. For example,

$$\text{NODE1}(N) = \text{NODE1}\ (N-1) + \text{INC}$$

The node number increment (INC) is the value specified with the element preceding the missing series of elements.

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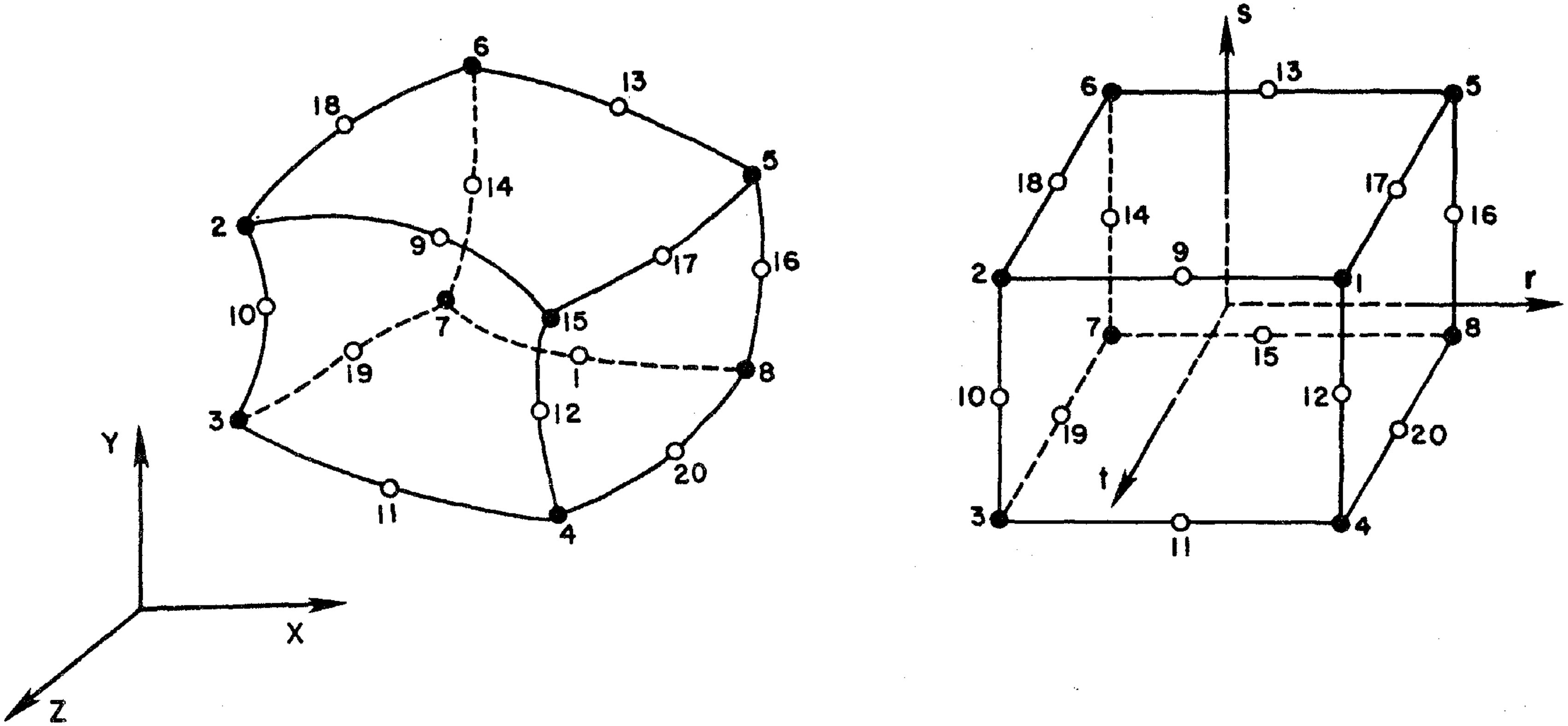


(a) 3D SOLID ELEMENT IN
GLOBAL X-Y-Z SYSTEM

(b) 3D SOLID ELEMENT IN
LOCAL r-s-t

FIG. 1 3D SOLID ELEMENT

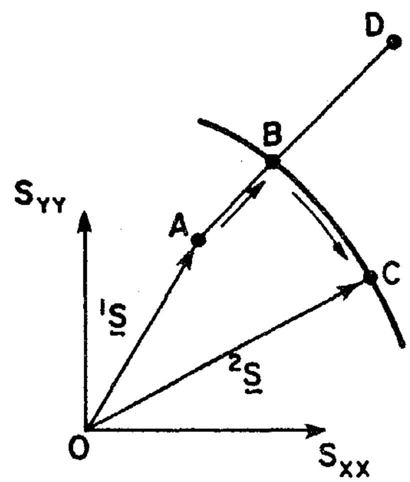


FIG. 2 STATE DETERMINATION

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